Spatiotemporal Distribution and Variation Characteristics of Annual Maximum Land Surface Temperature in China (2003-2018): Postprint

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Abstract

China has a vast territory, significant climate variations, and a large population. Investigating climate change in China within the context of global climate change is of paramount importance for safeguarding food security and ensuring sustained and stable socioeconomic development in China and worldwide. The annual maximum land surface temperature can mitigate interference from cloudy and rainy conditions in acquiring accurate land surface temperature data through thermal infrared remote sensing, exhibits relatively stable interannual variation, yet demonstrates high sensitivity to major land use transitions, droughts, heatwaves, and other extreme events. Based on MODIS (Moderate Resolution Imaging Spectroradiometer) land surface temperature products from 2003 to 2018, this study employs methodologies including climate tendency rate and linear correlation coefficient to analyze the spatiotemporal distribution and variation characteristics of the annual maximum land surface temperature across China.

The results reveal that: (1) The annual maximum land surface temperature in China exhibits a spatial distribution pattern characterized by higher values in the north and lower values in the south, with the absolute maximum located in the Turpan Basin of Xinjiang. (2) Analysis based on China' s climate zone divisions indicates that the temperate continental climate zone records the highest annual maximum land surface temperature, followed by the temperate monsoon climate zone with relatively high values, while the plateau mountain climate zone, subtropical monsoon climate zone, and tropical monsoon climate zone show comparatively lower values. The spatial distribution pattern of the annual maximum land surface temperature correlates with land cover types. (3) During 2003-2018, the temporal variation of the annual maximum land surface temperature in China demonstrates an overall weak cooling trend, with a climate tendency rate of -0.06 K · (10a)^-1, where cooling areas constitute 50.45%

of the total national territory. (4) The climate tendency rate displays a spatial pattern of higher values in the west and lower values in the east, with the warming trend in western regions being more pronounced than in eastern regions. Certain regions exhibit significant cooling trends, including central northern China, southern China, and the margins of the Tarim Basin, where such cooling is associated with vegetation cover changes.

Full Text

Preamble

Spatio-temporal Distribution and Variation Characteristics of Annual Maximum Land Surface Temperature in China during 2003–2018

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Abstract: China has a vast territory with significant climate differences and a large population. Studying climate change in China against the backdrop of global climate change is of great significance for maintaining global and Chinese food security as well as sustainable socio-economic development. The annual maximum land surface temperature (LST) avoids interference from cloudy and rainy weather on accurate thermal infrared remote sensing data acquisition, exhibits relatively stable interannual variation, yet remains highly sensitive to major land use transitions, droughts, and heat waves. Based on Moderate Resolution Imaging Spectroradiometer (MODIS) land surface temperature products, this study employs methods including climate tendency rate and linear correlation coefficient to analyze the spatio-temporal distribution and variation characteristics of annual maximum LST in China. The results show: (1) The annual maximum LST in China exhibits a spatial distribution pattern of high values in the north and low values in the south, with the highest value located in the Turpan Basin of Xinjiang. (2) Analysis of the spatial distribution according to China' s climate zones reveals that the temperate continental climate zone has the highest annual maximum LST, followed by the temperate monsoon climate zone, while the plateau mountain climate zone, subtropical monsoon climate zone, and tropical monsoon climate zone have lower values. The spatial distribution pattern of annual maximum LST is correlated with land cover types. (3) From 2003 to 2018, the temporal variation of annual maximum LST in China overall shows a weak cooling trend with a climate tendency rate of -0.06 $K \cdot (10a)^{-1}$, with cooling areas accounting for 50.45% of the total national area. (4) The climate tendency rate shows a spatial pattern of high values in the west and low values in the east, with a more pronounced warming trend in the western region than in the east. Some regions exhibit significant cooling trends, such

as central northern China, southern China, and the edges of the Tarim Basin, where cooling is related to vegetation cover changes.

Keywords: annual maximum land surface temperature; time series; spatio-temporal variation; MODIS

Introduction

China is located in eastern Eurasia and west of the Pacific Ocean, with a vast territory spanning large longitudinal and latitudinal ranges. Combined with land-sea thermal differences, China exhibits substantial climate variation. In recent years, under the background of global climate change, research on China' s climate change has become extremely important. Land surface temperature (LST) is the direct driver of longwave radiation and turbulent heat flux exchange at the land-atmosphere interface and represents one of the most important parameters in physical processes of surface energy and water balance. It has been identified by NASA and other international organizations as one of the most critical Earth system data variables, serving as a key input for various climate, hydrological, ecological, biophysical, and biogeochemical studies.

Many studies on global climate are based on meteorological station data. However, satellite-retrieved LST differs from near-surface atmospheric temperature. Due to the weak thermal conductivity of the atmosphere, atmospheric warming occurs much more slowly than surface warming. Ground stations conduct point-based observations, and the selected points significantly influence results. The uneven distribution of meteorological stations in extreme climate regions and the difficulty of maintenance increase errors in ground station temperature applications. Domestic and international scholars have used LST to provide theoretical support for climate change research, conducting long-term time series analyses of mean LST values and global LST thermal anomalies.

Satellite-based retrieval of LST via thermal infrared remote sensing dates back to the 1970s. To improve retrieval accuracy, many studies have proposed different LST retrieval algorithms to reduce the influence of various factors such as emissivity and atmospheric effects, including the generalized split-window algorithm, day/night algorithm, and temperature-emissivity separation algorithm. These algorithms yield more accurate LST data products that help us deeply understand dynamic changes in global land, ocean, and lower atmosphere.

The MODIS instrument, launched in 1999 on the Terra satellite and in 2002 on the Aqua satellite, is an important instrument in NASA' s Earth Observing System for monitoring global biophysical processes. Terra crosses the equator from north to south at approximately 10:30 local time (called the morning star), while Aqua crosses from south to north at approximately 01:30 local time (called the afternoon star). Aqua' s transit time of 01:30 is close to the daily maximum LST time. Moreover, data from 2003 to 2018 can meet the requirements for long-term time series studies of China' s annual maximum LST. This study uses MODIS/Aqua LST data products to extract annual maximum LST values and analyze their spatio-temporal distribution and variation characteristics in China.

Numerous studies have shown that satellite-derived maximum LST contains unique and richer information compared with general LST data. This data is highly sensitive to major land use transitions, heat waves, droughts, and vegetation information. Although continuous satellite-derived LST typically exhibits large spatio-temporal variations due to weather changes (wind speed, cloud cover, humidity, etc.), the annual maximum LST highlights correlations with extreme climate events and major land cover changes. For a specific region with unchanged land cover type, the interannual variation of maximum LST remains relatively stable. Mildrexler et al. analyzed the special properties of annual maximum LST and its correlation with heat waves, droughts, and ice melting but did not conduct time series analysis of annual maximum LST. Other studies have conducted long-term time series analyses of mean LST values, but the large data volume creates difficulties.

This study uses MODIS LST data products to extract annual maximum LST values and analyze their spatio-temporal distribution and variation characteristics in China. Selecting data with the best quality to obtain annual maximum LST values effectively avoids data missing problems and provides reliable data support for long-term time series studies. This approach helps obtain spatio-temporal characteristics different from other LST studies, provides a basis for understanding spatio-temporal variation characteristics of LST in China during 2003-2018, and contributes to better understanding of land-atmosphere interactions and their climatic effects in China.

1.1 Data

The MODIS MYD11A1 LST data product was downloaded from NASA' s official data website (https://ladsweb.modaps.eosdis.nasa.gov). This dataset is the latest LST data product retrieved using the generalized split-window algorithm, which eliminates atmospheric influence. The dataset includes daytime LST data (LST_{{{Day}}*{{1km}}}), nighttime LST data (LST*{{{Night}}*{{1km}}}), and corresponding quality control data (QC*{Day}, QC_{Night}), with a spatial resolution of 1 km and temporal resolution of 1 day. Data preprocessing involved extracting daytime LST data and corresponding quality control data from scientific datasets, performing projection and format conversion, and converting count values to actual LST values using coefficients.

Data selection criteria included clear-sky conditions (QC_{day} = 0) with average emissivity error less than 0.02 and LST error less than 2 K. For pixels selected as annual maximum LST, a 3 km × 3 km moving window was used to retrieve data, requiring at least 5 valid data points within the window. Land cover type data were obtained from MODIS MCD12Q1 annual data, which includes multiple classification schemes. This study extracted International Geosphere-Biosphere Programme classification data (LC_{Type1}) from MCD12Q1 with a spatial resolution of 500 m. To match the LST data resolution, MCD12Q1 data were aggregated to 1 km. Land cover data help better understand the influence mechanisms of land cover on LST and other factors.

Vegetation data were obtained from MODIS MYD13A3 vegetation index products, which provide normalized difference vegetation index (NDVI), enhanced vegetation index (EVI), and quality information. The MYD13A3 data have a spatial resolution of 1 km and temporal resolution of 1 month. This study selected China-region NDVI data to quantitatively investigate vegetation impacts on annual maximum LST.

Additionally, vector data of China' s agricultural climate zoning were used to assist in analyzing spatio-temporal distribution characteristics of annual maximum LST. Latitude zonality (climate variation with latitude) caused by solar radiation distribution differences, longitude zonality (climate variation with longitude) caused by land-sea distribution, and vertical zonality (climate variation with altitude) caused by increasing mountain elevation all affect climate zoning. Based on average temperature, accumulated temperature, average precipitation, and other climate factors, China' s agricultural climate zones were merged and divided on the basis of Huang Bingwei' s agricultural natural regionalization. The agricultural climate zoning data can be downloaded from the Chinese Academy of Sciences Resource and Environmental Science Data Center (http://www.resdc.cn/). This data divides China into temperate continental climate zones, temperate monsoon climate zones, plateau mountain climate zones, subtropical monsoon climate zones, and tropical monsoon climate zones [Figure 1: see original paper].

1.2.1 Method for Obtaining Annual Maximum LST

Annual maximum LST is obtained by selecting the maximum value within the year under clear-sky conditions (quality control data = 0). The method is expressed as:

$$LST_{max} = \max(LST)$$

where LST_{max} is the annual maximum LST. In this study, LST represents daytime LST data at 01:30 under clear-sky conditions.

1.2.2 Time Series Trend Analysis Method for Annual Maximum LST

Climate Tendency Rate: This method can display temporal variation trends of climate elements by obtaining a simple linear regression equation using meteorological element data and time series to analyze how meteorological elements change over time:

$$Y = \beta_0 + \beta_1 X$$

where X is the time sequence (years 2003-2018 in this study); Y is the meteorological element, which is the annual maximum LST in this research; β_0 is the intercept of the linear regression equation; and β_1 is called the climate tendency rate with units of $\mathrm{K} \cdot (10\mathrm{a})^{-1}$. The regression coefficient' s sign indicates the variable' s linear trend. The least squares method is used to minimize residuals, with the calculation formula:

$$\beta_1 = \frac{n \sum_{i=1}^{n} x_i y_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{n \sum_{i=1}^{n} x_i^2 - (\sum_{i=1}^{n} x_i)^2}$$

where x_i is the i-th year in the time sequence; y_i is the annual maximum LST in the i-th year; n is the total number of years (16 years in this study). If $\beta_1 > 0$, the annual maximum LST increases with time; if $\beta_1 < 0$, it decreases with time. The larger the absolute value of the climate tendency rate, the more obvious the trend.

Linear Correlation Coefficient (r): In this study, this is used to test the significance of temporal sequence fluctuations in annual maximum LST. The calculation formula is:

$$r = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2 \sum_{i=1}^{n} (y_i - \bar{y})^2}}$$

where y_i is the annual maximum LST in the i-th year; $\bar{y}$ is the average annual maximum LST over the time sequence; x_i is the i-th year; $\bar{x}$ is the time mean; and n is the total number of years (16 years). If the r value passes the significance test, it indicates significant fluctuation in the annual maximum LST time sequence; otherwise, the fluctuation is not significant.

2.1.1 Spatial Distribution Analysis of Annual Maximum LST

This study analyzed the spatial distribution characteristics of annual maximum LST using China' s climate zoning. [Figure 2: see original paper] shows the spatial distribution of multi-year maximum values of annual LST in China from 2003 to 2018. The figure reveals that northwestern China has the highest annual maximum LST, followed by northern China, while southern China and the Qinghai-Tibet Plateau have lower values. The highest values in northwestern China form a sharp contrast with surrounding areas due to the blocking effect of high mountains that results in minimal water vapor, combined with less cloud cover in the northwest that allows strong absorption of solar longwave radiation, all contributing to higher annual maximum LST values. The Inner Mongolia region also shows relatively high values due to similar geographic conditions to northwestern China. In contrast, southern China experiences more precipitation and greater cloud cover, causing some data gaps, and higher vegetation coverage changes surface properties, resulting in lower annual maximum LST. Overall, the spatial distribution pattern of annual maximum LST shows increases from south to north with latitude and decreases from northwest to southeast with increasing precipitation.

At the regional scale, high values of annual maximum LST occur in desert areas of northwestern China. However, previous studies have rarely mentioned the location of the national maximum value and its interannual variation. This study found that the highest annual maximum LST region is located in the Turpan Basin of China, an intermountain basin on the southern slope of the eastern Tianshan Mountains in Xinjiang. [Figure 3: see original paper] shows the interannual variation of annual maximum LST in the Turpan Basin from 2003 to 2018, with values exceeding 351.8 K (78.7°C) throughout the study period. This is because the Turpan Basin is a typical graben basin and the lowest altitude region in China, with an average elevation of -156 m. Additionally, its inland location far from the ocean creates a temperate continental climate with hot, dry conditions. The Turpan Basin is China' s "heat pole," consistent with meteorological data showing summer maximum temperatures of 49.6°C, making it China' s hottest summer location.

2.1.2 Regional Analysis of Annual Maximum LST

Topography, precipitation, and latitude all influence LST. Therefore, based on China' s climate zoning, the country was divided into five climate zones: tropical monsoon climate zone, subtropical monsoon climate zone, plateau mountain climate zone, temperate monsoon climate zone, and temperate continental climate zone [Figure 1: see original paper] for regional analysis of annual maximum LST. The quartile plot of annual maximum LST in each climate zone [Figure 4: see original paper] shows that the temperate continental climate zone has the highest annual maximum LST with a mean value of 328.7 K, followed by the temperate monsoon climate zone with a mean of 317.2 K. The plateau mountain, subtropical monsoon, and tropical monsoon climate zones have lower values around 312.0 K with small differences. First, this is because north-south temperature differences in mainland China are relatively small in summer. Second, land cover type affects LST by altering surface albedo, evapotranspiration, carbon cycling, and greenhouse gas emissions, thereby influencing climate at local, regional, and global scales. Northwestern China is mostly covered by bare soil and grassland, while other regions have higher vegetation coverage with significant land cover type differences [Figure 5: see original paper]. The temperate continental climate zone' s highest annual maximum LST corresponds to its predominant bare land cover and low vegetation coverage, where strong solar radiation and evapotranspiration lead to higher LST. The temperate monsoon climate zone has relatively high annual maximum LST with main land cover types of grassland and farmland, which have weaker temperature regulation effects compared to forests. The tropical and subtropical monsoon climate zones have lower annual maximum LST values due to forest cover with high vegetation density that provides stronger cooling effects.

2.2.1 Interannual Variation Characteristics

Time series trend analysis of annual maximum LST (climate tendency rate and linear correlation coefficient) can highlight the impacts of land cover and vegetation on LST while excluding weather and seasonal influences. [Figure 6: see original paper] shows the spatial distribution of climate tendency rate and linear correlation coefficient of annual maximum LST in China from 2003 to 2018. Large-scale cooling exists in central northern China, with cooling also observed at the edges of the Tarim Basin oasis and in southwestern China. The linear correlation coefficient shows a similar spatial distribution pattern to the climate tendency rate. In [Figure 6: see original paper], blue areas represent regions with significant LST decrease, while red areas represent significant increase. Nationally, 49.55% of the area shows an increasing trend, but this trend is not significant. In contrast, cooling trends are evident in southern Shanxi and Shaanxi provinces and at the edges of the Tarim Basin. Other studies have also indicated cooling trends in central China and greening phenomena at the Tarim Basin edges. Additionally, small cooling trends appear in southwestern China, possibly related to increased aerosols.

Nationally, the mean climate tendency rate and linear correlation coefficient of annual maximum LST show a weak cooling trend , with cooling areas accounting for 50.45% of the country' s total area. This is associated with significant cooling trends in central China, the Tarim Basin edges, and southern China. The cooling trend is more significant than the warming trend at the national scale.

2.2.2 Regional Analysis of Interannual Variation

To further understand regional differences in temporal trends of annual maximum LST, this study conducted statistical analysis of time series trends in different climate zones. shows the climate tendency rate and correlation coefficient of annual maximum LST in different climate zones from 2003 to 2018. The results indicate that the Qinghai-Tibet Plateau shows a strong warming trend due to its special geographic location. The temperate continental climate zone shows a weak warming trend; although large areas show warming, the strong cooling trend at the Tarim Basin edges results in an insignificant overall warming trend. Other regions show varying degrees of cooling, most significantly in the temperate monsoon climate zone, with cooling also observed in tropical and subtropical monsoon climate zones.

The average annual maximum LST in this study shows a cooling trend, likely influenced by strong cooling in some regions such as parts of Shanxi and Shaanxi, the Tarim Basin edges, and southern China. This cooling is closely related to vegetation growth, as vegetation cover changes alter surface albedo, roughness, and soil moisture, affecting climate at different spatio-temporal scales. Generally, increased vegetation leads to lower temperatures. Central China shows obvious vegetation growth trends, and other studies have confirmed significant cooling phenomena in this region.

2.2.3 Correlation Analysis Between Significant Cooling Areas and NDVI

To analyze the correlation between significant cooling areas of annual maximum LST and NDVI, this study used MYD13A3 data to calculate annual maximum NDVI values from 2003 to 2018. Using the linear correlation coefficient formula, the correlation between annual maximum LST and annual maximum NDVI time series was computed. [Figure 7: see original paper] shows the spatial distribution of linear correlation coefficients between annual maximum LST and annual maximum NDVI in China from 2003 to 2018. Vegetation in southern Shanxi and Shaanxi and at the Tarim Basin edges shows significant increasing trends, consistent with other studies indicating vegetation increase at desert edges in northwestern China.

The linear correlation coefficient analysis results align with climate tendency rate results. The temperate continental climate zone shows a weak warming trend with a climate tendency rate of 0.09 $K \cdot (10a)^{-1}$, while the area passing significance tests accounts for only 7.20% . The plateau mountain climate zone shows a warming trend with a climate tendency rate of 0.56 $K \cdot (10a)^{-1}$, but the area passing significance tests is only 4.22%. The temperate monsoon climate zone shows a cooling trend with a climate tendency rate of -0.74 $K \cdot (10a)^{-1}$, with significant cooling areas accounting for 12.77%. The subtropical monsoon climate zone shows a more obvious cooling trend, with significant cooling areas accounting for 11.45%.

To analyze the correlation between annual maximum LST and NDVI in significant cooling regions, this study selected three significant cooling regions (I, II, III) [Figure 7: see original paper]. shows the linear correlation coefficients between annual maximum LST and annual maximum NDVI in these three regions. The linear correlation coefficient of annual maximum LST significantly decreased while that of NDVI significantly increased, with the NDVI increase area far exceeding the LST decrease area. This indicates a strong negative correlation between climate change and vegetation in regions with significant LST decrease in China.

[Figure 8: see original paper] shows the interannual variations of annual maximum LST and NDVI in regions I, II, and III from 2003 to 2018. Annual maximum LST shows an obvious cooling trend while NDVI shows a significant increasing trend. presents the linear regression between annual maximum LST and NDVI, showing a very obvious negative correlation between mean annual maximum LST and mean annual maximum NDVI.

3 Conclusions

Based on MODIS LST products and using climate tendency rate and linear correlation coefficient methods, this study analyzed the spatio-temporal variation patterns of annual maximum LST in China. The results indicate:

(1) Annual maximum LST values are highest in northwestern China. Differences in land cover types between southern and northern regions result in lower annual maximum LST in southern China compared to northern China. The highest annual maximum LST is located in the Turpan Basin of Xinjiang. The Turpan Basin is situated in northwestern China within a temperate continental climate zone with low precipitation and dry climate, and it is the lowest altitude region in China, making it China' s hottest area.

(2) According to China' s climate zoning analysis, the temperate continental climate zone has the highest annual maximum LST (mean value of 328.7 K), followed by the temperate monsoon climate zone. The plateau mountain, subtropical monsoon, and tropical monsoon climate zones have lower values. The spatial distribution pattern of annual maximum LST is closely related to land cover types, with different land cover types exerting varying degrees of influence on annual maximum LST.

(3) Long-term time series analysis of annual maximum LST shows an overall weak cooling trend, with a national climate tendency rate of -0.06 $K \cdot (10a)^{-1}$. Cooling areas account for 50.45% of the national total. The climate tendency rate shows a spatial pattern of high values in the west and low values in the east, with more obvious warming trends in western regions. Some areas show significant cooling trends, particularly central northern China, southern China, and the edges of the Tarim Basin, where cooling is related to vegetation growth. Vegetation cover changes affect climate by altering surface albedo, roughness, and soil moisture at different spatio-temporal scales.

(4) Except for East China, NDVI growth across the country is in a positive trend, with the most obvious growth in significant cooling regions. However, weak positive correlation areas between annual maximum LST time series and NDVI also show positive correlation, indicating that factors influencing annual maximum LST increase require further study. Some regions show simultaneous growth in both vegetation and annual maximum LST, suggesting that land use changes other than vegetation also affect annual maximum LST and require further investigation.

This study provides long-term time series research on annual maximum LST that previous studies lacked. Other long-term time series studies focused on daily, monthly, or annual mean LST values, but did not analyze annual maximum LST. Annual maximum LST excludes weather influences and has different practical significance than mean LST, being more closely related to land cover, drought, heat waves, and major land use changes. This study demonstrates a strong correlation between annual maximum LST and land cover changes, indicating that annual maximum LST variation is closely related to recent afforestation projects. However, quantitative research on how afforestation affects LST changes requires further study.

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Note: Figure translations are in progress. See original paper for figures.